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13. ABSTRACT *(Maximum 200 words)* A compact soft X-ray laser (SXL) can be designed combining results of Princeton Plasma Physics Laboratory (PPPL) and Rutherford Appleton Laboratory (RAL). At PPPL, gain at 18.2nm was demonstrated in a carbon plasma pumped by a low energy laser, with no magnetic field. The lasing length was limited by refraction or nonuniformity in the plasma. In the RAL germanium soft X-ray laser, two adjacent lasing media, pumped from opposite directions, compensated refraction. PXL adopted RAL's concept to the carbon SXL to build a "table-top" 18.2nm laser with output pulse around 20mJ. It will be two orders of magnitude more intense than a laser-produced plasma, with radiation in 10 mradian. Phase I resulted in: design and construction of a twin-target system, set-up of a new experiment on the optical table, test of the new chamber, reduction of pulse duration to 1.7 ns. In Phase II, PXL will achieve high gain in the refraction-compensated, twin-target system and construct a prototype.

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FINAL PROJECT SUMMARY FOR SDIO

"PORTABLE" SOFT X-RAY LASER

Principal Investigator: Leonid Polonski
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Abstract

A very useful compact soft X-ray laser (SXL) can be constructed based on the achievements of two laboratories: Princeton Plasma Physics Laboratory (PPPL) and Rutherford Appleton Laboratory (RAL). In the PPPL experiment, gain at a wavelength of 18.2 nm was demonstrated in a recombining carbon plasma pumped transversely by a Nd/YLF laser of relatively low energy *and without the use of an external magnetic field.* However, the effective lasing length was probably limited by refraction effects in the plasma or its nonuniformity, or both. In the RAL experiment for collisionally excited germanium soft X-ray laser, two adjacent lasing media, pumped from opposite directions, provided compensation for the refraction. The PXL Team proposed to adopt RAL's concept to the recombination SXL in order to build a compact, "table-top"18.2 nm laser with output pulse energy around 20 μJ. It will be about two orders of magnitude more intense than a laser-produced plasma, with the radiation concentrated in a 10 mradian cone. The beam divergence will decrease another three orders of magnitude with development of a cavity.

Following the Phase I plan, the following work was performed:

- design and construction of a twin-target system,
- design and set-up of a new experiment on the optical table,
- test of the new chamber,
- reduction of the pumping pulse duration to 1.7 ns.

As a result, the whole system is prepared to continue research and to achieve high gain in the refraction- or nonuniformity-compensated, twin-target system in Phase II.

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1. Research Objectives of Phase I Proposal

The over-all technical goal of the present work is to compensate for the effects of decreasing gain G with increasing length L of lasing medium to achieve a significant increase in the one-pass gain, GL, in the "table top" soft X-ray laser. The fact that GL has thus far not followed the theoretically expected behavior with increasing plasma length is probably caused by the nonuniformity of the plasma column, associated with a nonuniform intensity of the drive laser on the target surface, and by refraction of X-rays due to radial gradients in the plasma. The development of a system with two adjacent targets pumped from opposite directions to compensate for both nonuniformity and refraction, while retaining the successfully demonstrated gain in a recombing carbon plasma without magnetic field, will achieve the above objective.

The Phase I goals have been accomplished:

- To design and construct a twin-target system.
- To test the new chamber, using PPPL facilities.
- To investigate the possibility of modifying the drive Nd-laser at PPPL, including beam apodization and shortening of the pulse duration to 1-1.5 ns.

Most importantly, the Phase I work has resulted in a novel experimental arrangement set up on the optical table with the possibility for high precision alignment of the entire system in order to increase the total one-pass gain in a two length lasing medium, $G(L_1+L_2)$.

The specific goals of Phase I are necessary initial steps in the accomplishment of the broader objective to be pursued in Phase II: a highly reproducible one-pass gain ($GL \geq 4.5$) for the 18.2 nm transition of CVI. This will, in turn, make the use of a cavity feasible. The same techniques could be used for 15.4 nm in AlXI and 12.9 nm in SiXII.

Success in reaching these objectives should result in the ultimate goal of this work: a prototype "table-top" soft X-ray laser.

2. Introduction

We proposed a new design of a soft X-ray laser (SXL) which combines an existing design for a portable SXL based on the carbon gain-medium [1], with a solution to the problem of compensating gain-decreasing effects in such plasmas, developed at the Rutherford Appleton Laboratory (RAL) [2]. The proposed compact, relatively inexpensive 18.2 nm SXL will have an output power of 10-20 μJ using a 10 J, 1 - 3 ns pulse from a pump laser. This SXL will have its output concentrated in a ~10 mradian cone, without a cavity, or in a ~10 μradian cone with a cavity, and whose intensity will be, respectively, about two or five orders of magnitude greater than a laser-produced soft X-ray plasma source powered by the same pump laser.

Here we would like to discuss the Princeton experiment as, in our view, it opened the path to a really small X-ray laser. In this experiment, a line-focused laser beam interacts with a carbon target for the 18.2 nm laser. In this manner, a column of hot carbon plasma is created in which a substantial fraction of carbon ions is fully stripped. Subsequent radiation and expansion cooling produce rapid three-body recombinations, which preferentially populate CVI ion levels of high principal quantum number.

The recombined electrons then cascade rapidly to lower principal quantum number levels. At the same time, the lowest excited levels, particularly the n=2 level, which has a large radiative transition rate, is rapidly depopulated by the strong radiative transition resulting in a population inversion between levels 3 and 2 and 4 and 2 with much higher gain for 3 -> 2 transition at 18.2 nm. This short lived inversion leads to amplified spontaneous emission and lasing at CVI 18.2 nm. In the first experiments a gain as high as 8 ± 2 cm^{-1} on CVI 18.2 nm was measured with a pumping Nd/YLF laser energy of 25 J

(~15 J on the target) and a magnetic field of 50 kG, using a rotatable cylindrical target system [3].

During the course of these experiments, a gain of 4.5 cm^{-1} for the same transition for 4.5 mm plasma was observed using only 6 J of the drive laser *without magnetic field* [4,5]. This was a crucial observation which opened the path to the development of a very compact ("portable") soft X-ray laser operating at 18.2 nm. However, the gain-length product GL = 2 achieved in this low pumping energy experiment provides only about a factor of 2 higher in intensity of stimulated emission for 18.2 nm line in comparison to its spontaneous emission for the laser-produced plasma source, powered by the same size pumping laser. The increase of gain-length (GL) to 4.5 will increase the ratio of intensity of stimulated emission of 18.2 nm line over its spontaneous emission to the value ≈ 10. With a reproducible gain-length GL ≈ 4.5, we will be able to implement a cavity with multilayer mirrors of reflectivity ≈ 25% (of course, with higher reflectivity of the mirrors, GL can be even lower). Hence, our main goal is to obtain highly reproducible GL ≥ 4.5 with only 10 J of pumping energy of the Nd/Glass laser.

In order to achieve this goal, the Princeton University team in cooperation with the PXL team has conducted experiments with a 7.5 mm laser carbon target, which was later replaced by a 12 mm long carbon target. In the 7.5 mm long target, a gain of 4.5 cm^{-1} was achieved (GL ≈ 3.4). However, with the 12 mm target GL did not increased significantly, although from time to time, GL ≈ 4 was reached.

The geometry of the experiments is shown in Fig. 1. A pumping laser beam (1) irradiates a carbon cylindrical target (2); during interaction of laser beam with solid material a dense and hot plasma column (3) is created, which has a semicylindrical shape due to line focusing of the pumping beam; stainless-steel blades (4) are placed at a distance d_2 from the target to increase the plasma cooling speed by

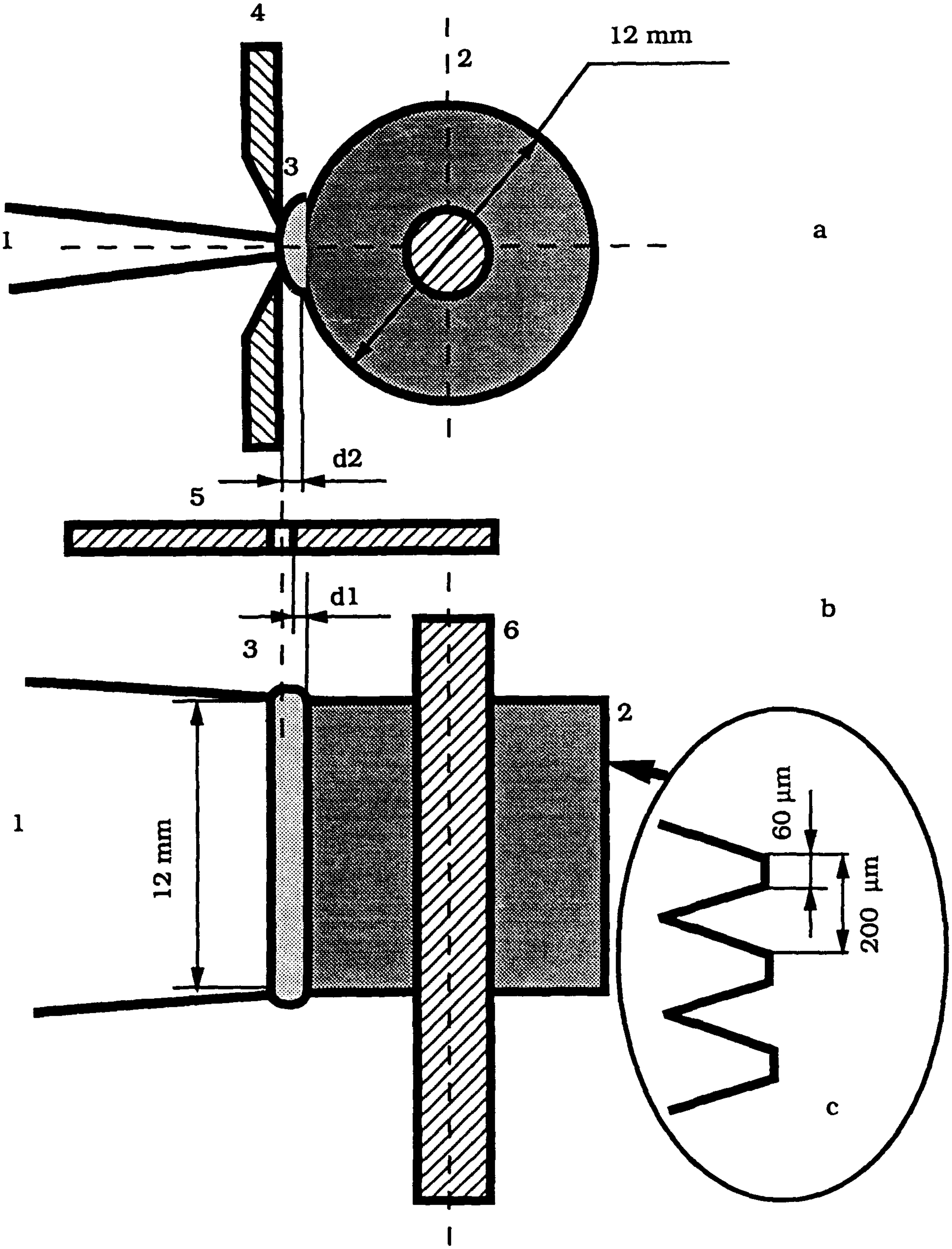


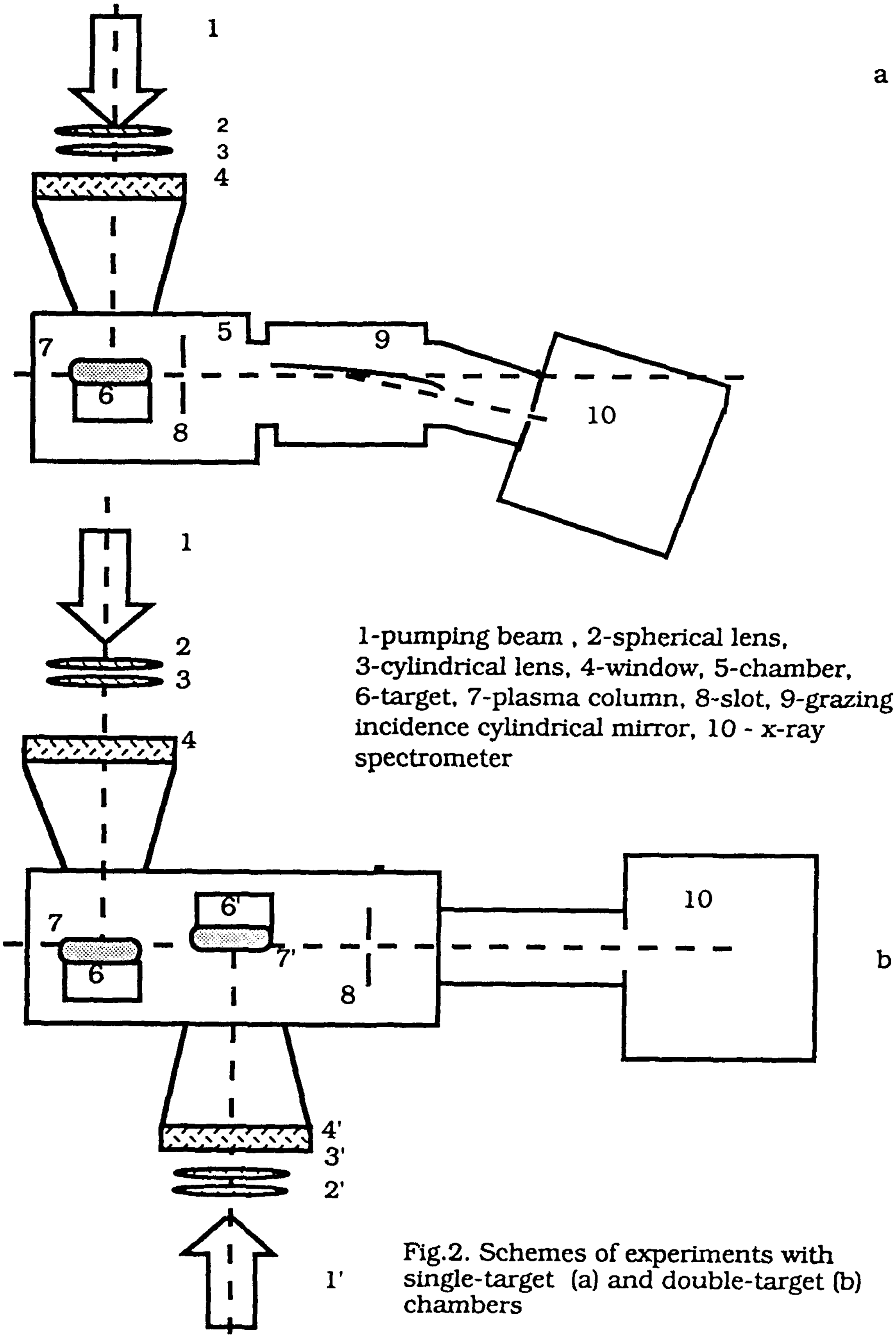
Fig.1.Geometry of the target irradiation (a, b) and the shape of its surface (c).

thermal conductivity and intense radiation losses of iron ions, which ablate into the plasma; the X-ray radiation from the plasma region optimal for lasing is determined by properly positioning slot (5) at the distance d_1 from the target surface.

These attempts to increase the gain-length of the medium have been thwarted, we believe, by the nonuniformity of the plasma and refraction effects . The gain regions are so narrow, typically 100 μm wide, that small changes of electron density along the plasma column as well as in its radial direction restrict the effective length of the gain region. However, experiments at RAL demonstrated a simple, but effective method of overcoming this problem for collisionally pumped SXL in germanium [2]. Two adjacent lengths of lasing plasma medium are pumped from opposite directions, compensating these effects

In Fig. 2 we present a schematic configuration of Princeton's earlier experiment with a single target (a), and the recent experimental set-up based on the PXL approach with a twin target (b). In both schemes, the pumping laser beams (1) are focused by spherical (2) and cylindrical (3) lenses to provide a linear focal configuration on the surface of the target (6). The pumping radiation is focused on the target through the window (4). Radiation from the plasma column (7) passes through the slot selecting the region of maximum gain, and is collected and focused by a grazing incidence cylindrical mirror on the slit of the X-ray spectrometer (10).

In PXL's twin-target scheme (Fig. 2b), the new chamber with the additional target (6'), focusing optical system (2', 3') and window 4' for the second beam is used. The collecting cylindrical mirror is removed and the plasmas are centered relative to the optical axis of the spectrometer. Although the notion is simple, the alignment of the two plasmas poses a technological challenge: the alignment will require precisions of ≈10 μm in position and ≈1 mradian in directional accuracy. These constraints were taken into account during the design and construction of the twin-target chamber.



1-pumping beam , 2-spherical lens, 3-cylindrical lens, 4-window, 5-chamber, 6-target, 7-plasma column, 8-slot, 9-grazing incidence cylindrical mirror, 10 - x-ray spectrometer

Fig.2. Schemes of experiments with single-target (a) and double-target (b) chambers

The variation of the intensity of spectral lines in the vicinity of 18.2 nm has been recorded, as described in [6]. Assuming that the plasma length is the same as the length of the target, the gain G for 18.2 nm line was estimated from the relation

$$I \sim \{\exp(GL) - 1\}^{3/2} / \{GL \exp(GL)\}^{1/2} \tag{4}$$

For a smooth cylindrical target, with three sections of L_2 = 4, 8 and 12 mm, maximum gain was observed at a distance of 0.8 - 1.0 mm away from the target surface. Higher gain at locations closer to the target surface was measured for a multiple-fin target. These facts indicate faster expansion and greater cooling rate of the plasmas using finned targets. The purpose of the fins is to enhance the expansion cooling by creating a series of small initial plasmas. Later, in the recombining phase, these initially-separated plasmas become connected to form a continuous gain region. This concept was first demonstrated in [7]. We plan to use such targets with a new twin-target chamber in Phase II experiments.

3. Research Carried Out

3.1. *Preliminary experiments*

Preliminary experiments during Phase I were conducted by the PXL team with the "old" vacuum chamber, containing one target. The main goal of these experiments was to explore a range of positions for the target, blades, and slot and the accuracy of these adjustments. This information was necessary for the design of the new twin-target chamber in order to obtain high reproducibility of the gain. It was found that the optimum range for the distance between the target surface and the nearest slot edge was d_1= 0.4-0.8 mm, with the distance between the target surface and the blades d_2 =0.8-1.2 mm, and the slot width s=0.2 mm. The slot - target distance was 2 cm along the target - spectrometer path.

During the experiments, gratings of 1200 and 600 groove/mm were used in the soft X-ray spectrometer. The first of these allows more detailed spectra to be recorded, but the second provides simultaneous measurements of the lasing line at 18.2 nm as well as a reference nonlasing line (13.5 nm) of H-like carbon ion CVI. This simultaneous recording of both lines is important when there are significant fluctuations of the plasma parameters. A rectangular or square apodizer was placed in the driving laser beam in some experiments to improve the uniformity of the line focus.

Different target geometries were tested in the experiments: smooth and finned cylinders (Fig. 1c). Finned cylindrical carbon targets, with fin width varying from 60 to 200 μm, were used. In these experiments, the previous results of [6] were confirmed.

3.2. Design and construction of a twin-target system

3.2.1. Twin-target chamber

The chamber was designed by the PXL team to compensate for significant soft X-ray refraction in the plasma column and to provide more flexibility in the illumination of the target in order to increase GL. It consists of two independent carriages, each of which can be precisely translated normal to the chamber axis. The translations are accomplished with microscrews with a precision of about 5 μm. The chamber has four windows: two of them for the pumping laser beams, one - for soft X-ray radiation output, and the second, for alignment with the He-Ne laser (Fig. 3).

The targets can be rotated along the target axis under vacuum in order to provide a fresh surface for each pulse. This is achieved by vacuum-sealed stainless steel polished rods, and two pairs of conical gears. The precision of rotation is 1-2°. The size of the cylindrical target is the same as in previous experiments, both the diameter and the length are equal 12 mm.

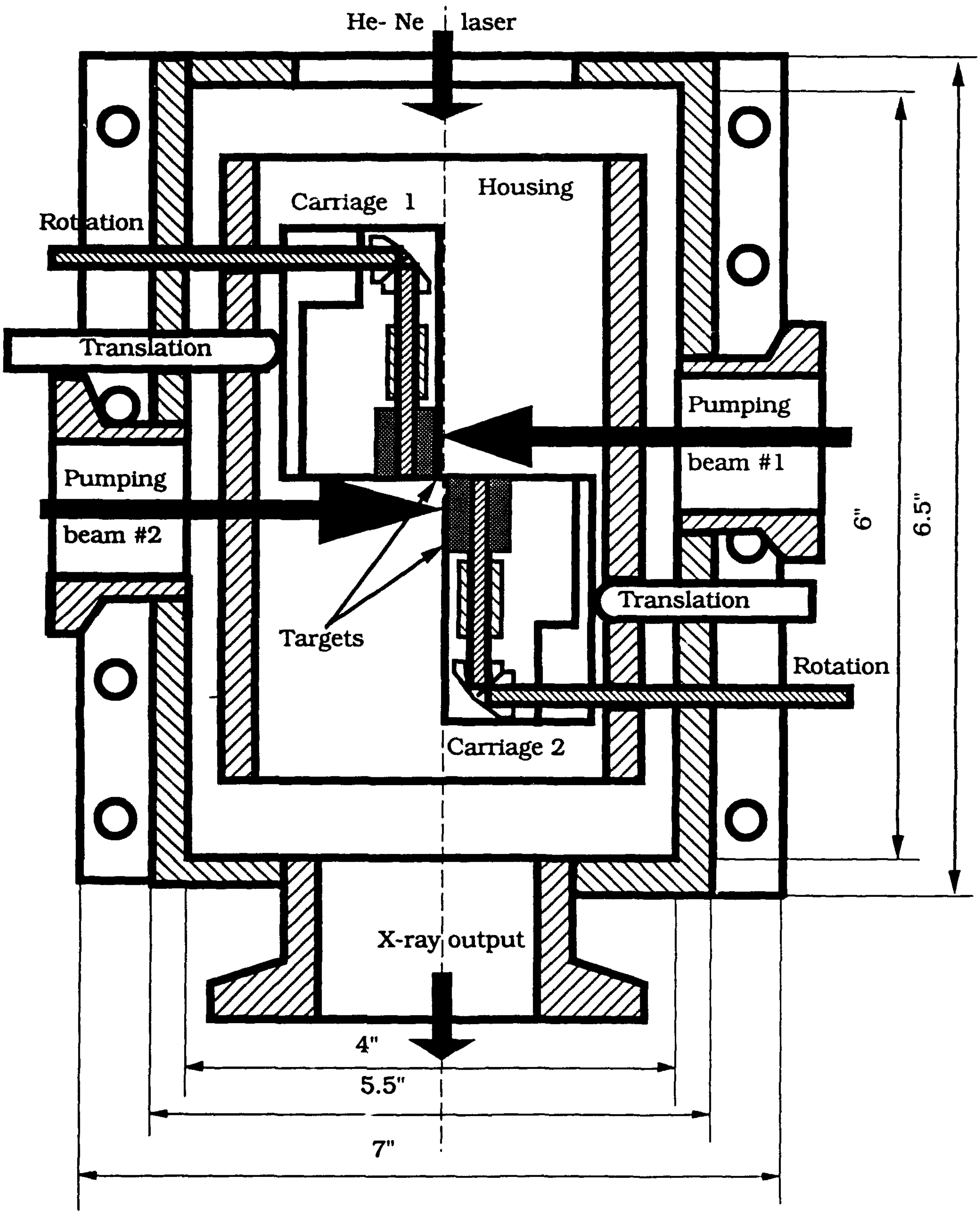


Fig. 3. Twin-target chamber (top view).

3.2.2. Optical scheme and arrangement of elements for the twin-target system

A layout of the new experimental setup, made by the PXL team during Phase I, is presented in Fig. 4. The system is placed on an optical table, 10'x4'; it consists of the twin-target chamber with high vacuum system, X-ray spectrometer (Minuteman) with its own high vacuum system, and the optical sub-system, including 6 mirrors for transporting pumping radiation and two identical focusing systems.

Synchronization of two pumping beams on the targets is achieved by using an optical delay. Photographs of the experimental setup and separate details are shown in Figs. 5-7.

3.3. Tests of the new chamber

The tests were carried out to check the chamber performance and to make sure of the correct interaction of all parts of the new experimental setup. During the tests the vacuum, alignments and feasibility of the whole system were examined.

- High vacuum (10^{-6} Torr) was achieved in the chamber during testing. The chamber could be evacuated in 20-30 minutes.
- All alignments were checked under vacuum with He-Ne auxiliary laser and smooth fine translations and rotations of the targets were achieved. Long time vibrational stability of the optical setup was tested by observing reflections of the He-Ne laser beam on the same location of the wall during several days.
- Feasibility tests were performed for each target. Since we had only one set of focusing optics, these optics were relocated in order to irradiate the targets in turn. As a result X-ray spectra in the wavelength range 13.5 - 18.5 nm were recorded. One of them is shown in Fig. 8.

Hence, the tests were successful and a new experimental setup with the twin-target chamber, as shown above, is prepared for

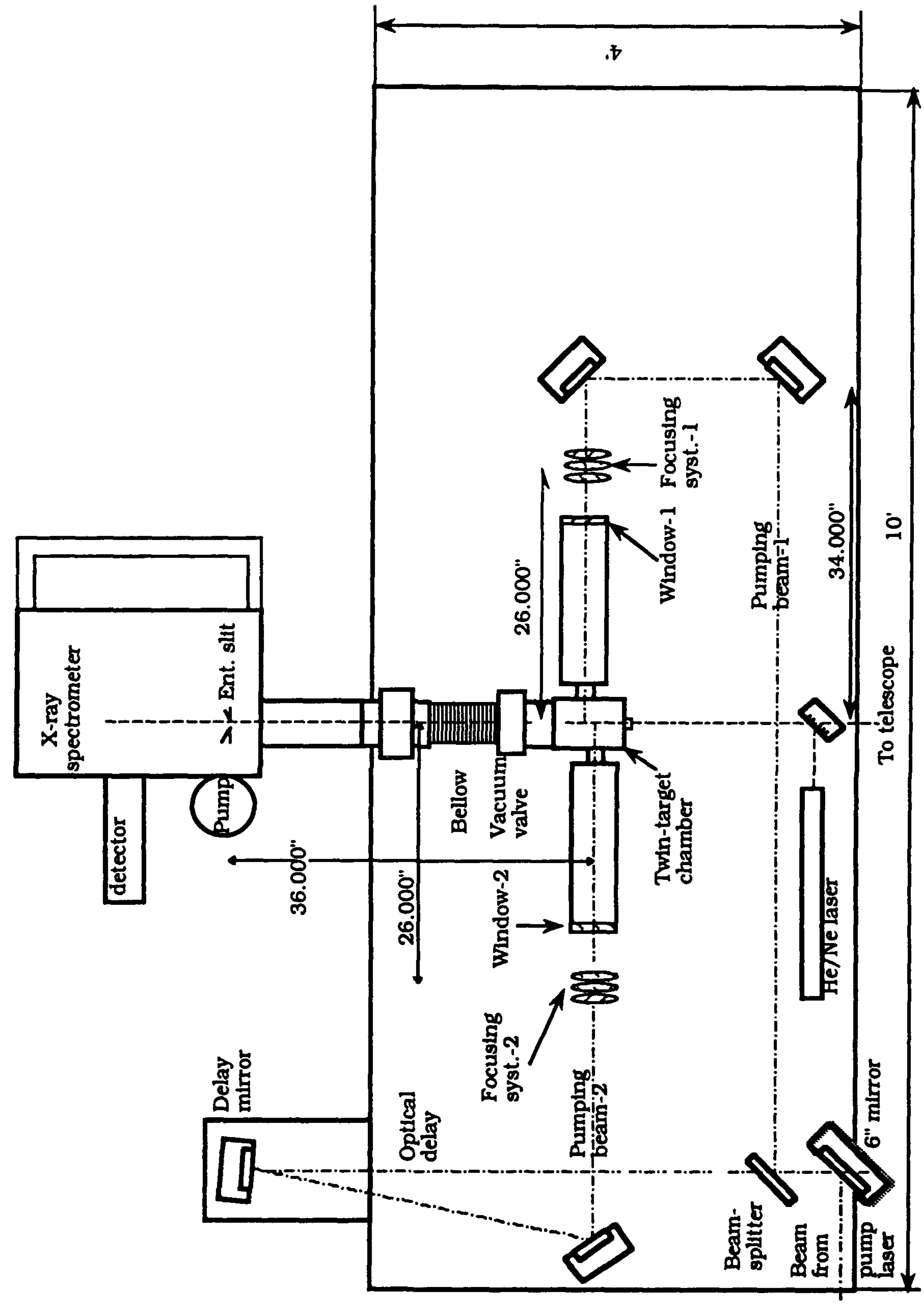


Fig. 4. Experimental setup for "portable" soft x-ray laser with twin-target chamber.

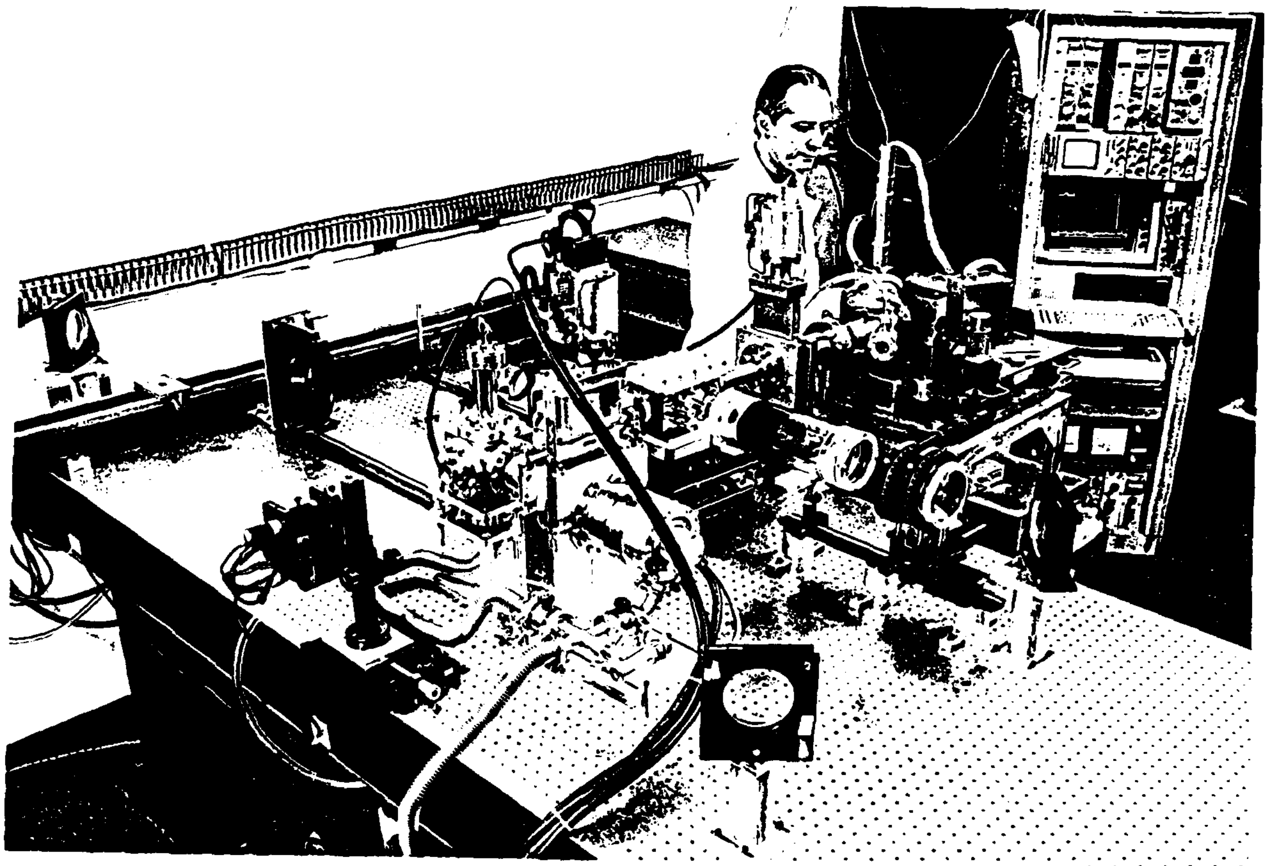


Fig. 5. Experimental setup

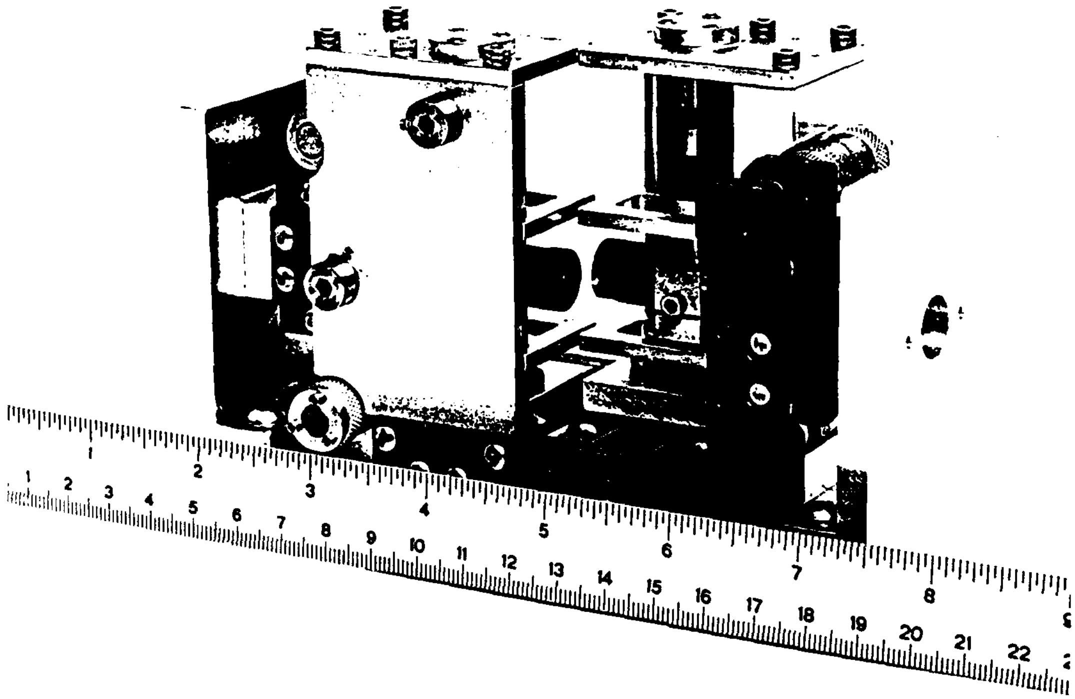


Fig. 6.Target assembly

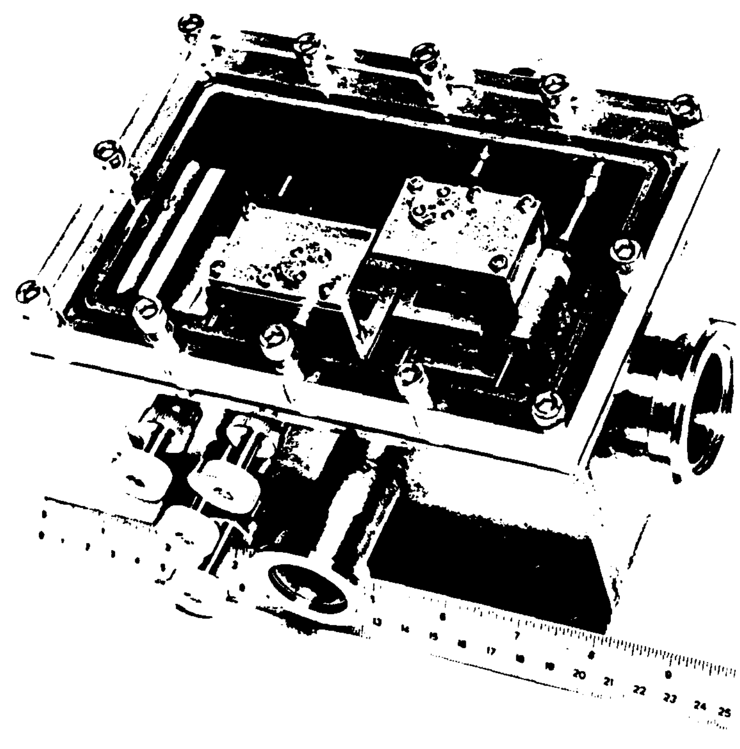


Fig. 7.Twin-target chamber

experiments during Phase II. (The second set of required focusing optics will be purchased at the beginning of Phase II).

3.4. Modification of the drive Nd-laser

In a freely expanding plasma, without magnetic field, use of shorter pumping pulses might be more efficient for faster ionization of ions (during the heating period) and faster cooling during the recombination period. This should lead to a higher population inversion and gain. It is for this reason that we have investigated pulse-shortening in Phase I.

The drive laser pulse duration is defined by the length of the cable line, connecting two Pockels cells inside the slicing device. Measurements were accomplished with a MRD 721 photodiode and a Tektronix 7934 oscilloscope. Calibration of the measuring circuit was performed with a picosecond laser (t_p= 150 ps) and 1 GHz sinusoidal electronic generator. The calibration oscillograms are presented in Fig. 11. The half-width of the recorded pulse is t_{rc} = 1.2 ns. This value defines the time resolution of the diagnostic used and should be taken into account, when the measured pulse has a duration t_p of the same order of magnitude as t_{rc}, on the basis of the following formulae

$$t_p = (t_r^2 - t_{rc}^2)^{1/2} \quad (5)$$

The original cable (1 m) provides a pulse duration t_p= 3.5 ± 0.5 ns (Fig.12a) while the cable shortened by a factor of three gives t_p=1.7 ± 0.5 ns (Fig.12c). The corresponding rejected pulses are shown in Fig. 12b, d. The energy of the oscillator pulse after the slicer was decreased from 2 to 0.6 mJ, when the pulse was shortened.

The pulse duration achieved appears to be the limit for the present slicer scheme, because further decrease of the cable length down to 10 cm gives no further pulse shortening.

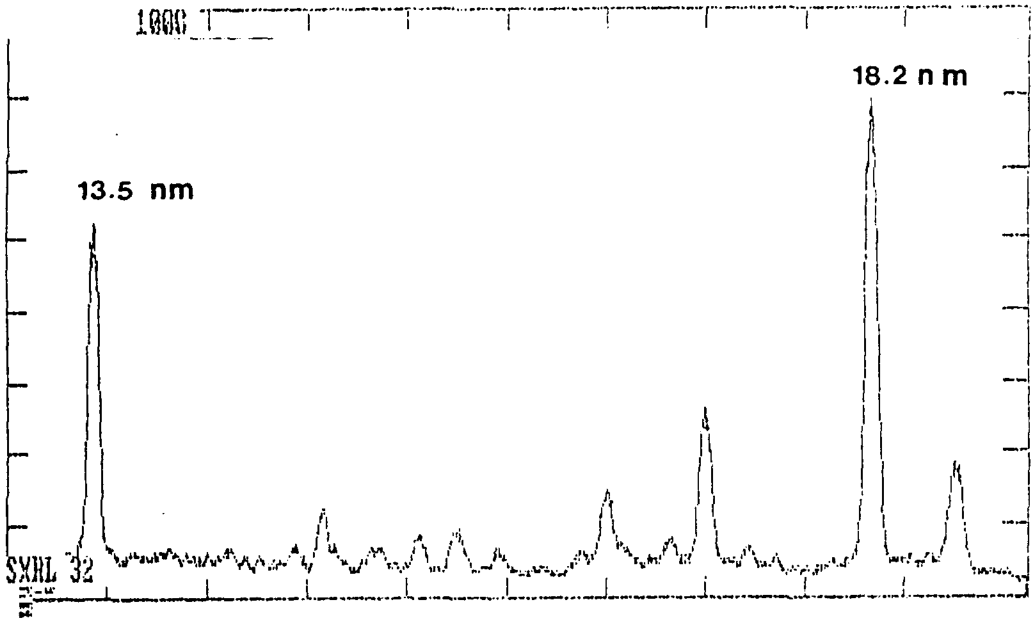


Fig. 8.Test X-ray spectrum from the new chamber

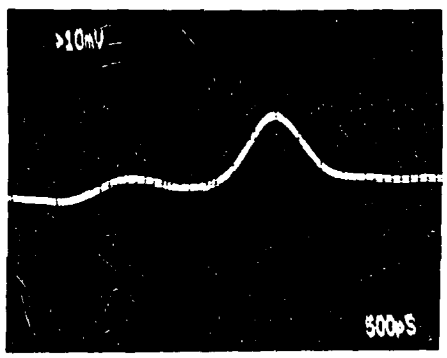


Fig. 9. A subnanosecond laser pulse, recorded by a MRD 721 photodiode and a Tektronix 7934 oscilloscope.

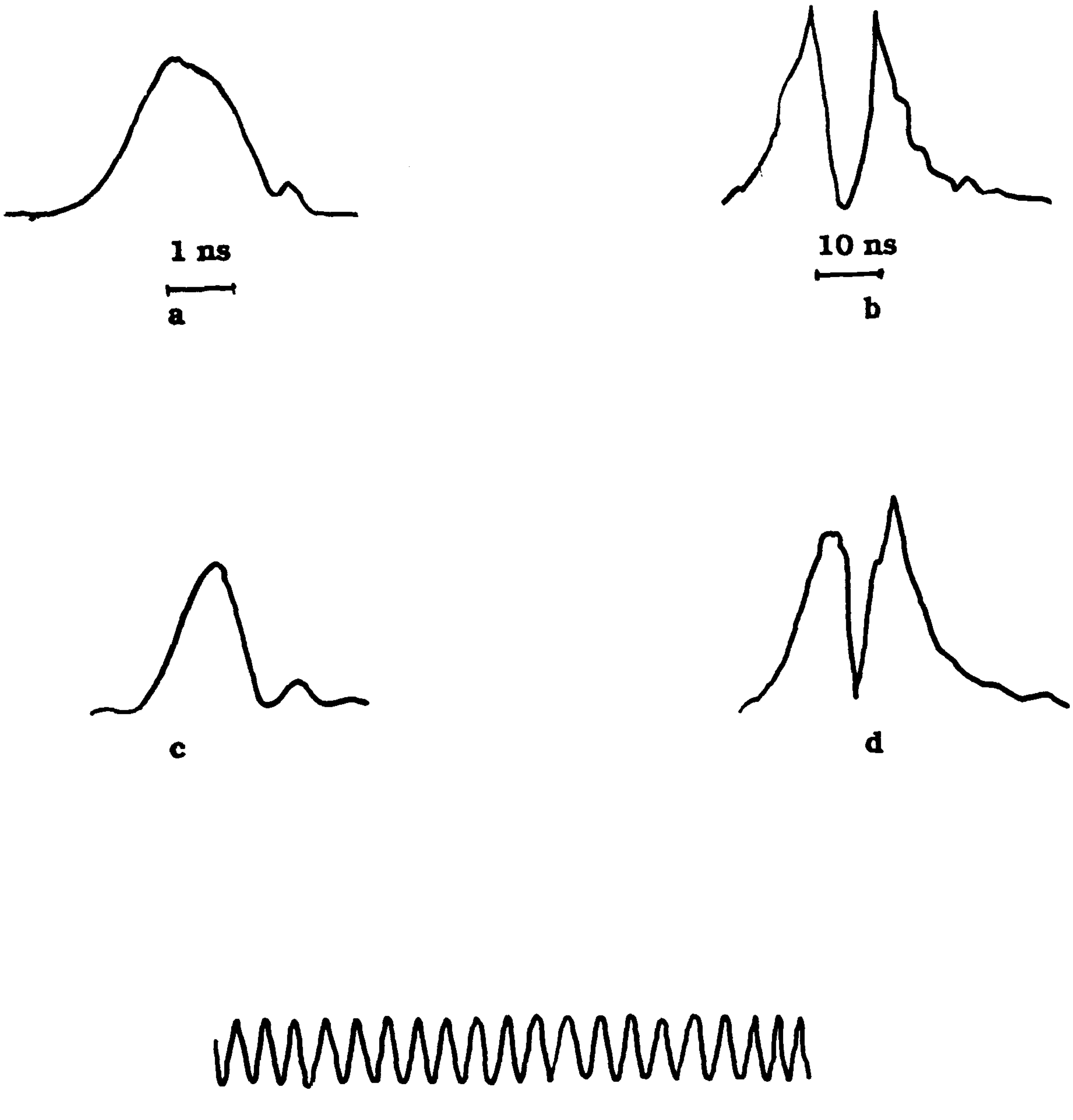


Fig.10. The drive laser pulses: original (a), shortened (c), rejected pulses for the same conditions (b.d), and 1 GHz sinusoid (e)

4. Research Findings and Implications

During Phase I, PXL scientific and technical personnel made the following contributions to the proposed development of the compact ("portable") soft X-ray laser (SXL):

(a) Studies of gain spatial distribution for the "old" target chamber (previously built by the Princeton University team in cooperation with PXL). These studies revealed not only the size of the region where the maximum gain occurs and the effect of the target configuration on the gain distribution, but provided also very important information about the necessary accuracy of setting the target position, viewing slot, blades and spectrometer in order to achieve reproducible gain medium conditions.

Such information was crucial in designing a new twin-target chamber. It also revealed that the rather crude design of the "old" one-target chamber could have significantly to the problems with irreproducibility of the gain due to the insufficient accuracy of re-setting positions of the target and viewing slot.

(b) The design and construction of a new two-target assembly chamber, with high precision mechanical alignment, is critical for gain generation parameters. The PXL team proposed this design in order to compensate for the effects of refraction in the plasma. The idea of compensation of refraction in line focus configuration was first demonstrated in a collisionally pumped germanium SXL at the Rutherford Laboratory (RAL) and is presently adopted to the recombination SXL.

(c) The design and set-up of a novel experiment on the optical table with much better access to the target assembly and the possibility of high precision alignment of the entire system (see photo-Fig. 5).

(d) Shortening of the Nd/Glass laser pumping pulse. The shortening of the pumping pulse is expected to have a positive effect for more efficient production of fully ionized ions and for faster plasma cooling, which should lead to a more efficient use of the pumping energy. On the other hand, it may decrease the duration of lasing which would not be desirable from the point of view of cavity design. We will further experimentally explore the effects of pulse duration in the course of Phase II.

5. Technical Feasibility Conclusions

In Phase I, we have successfully:

- Designed and constructed a twin-target system.
- Designed and set up a new experiment on the optical table.
- Tested the new chamber.
- Shortened the pulse duration to 1.7 ns.

A sophisticated experimental set-up has been established for research and development in Phase II which should result in a prototype of the "table-top" soft X-ray laser with the specifications discussed earlier.

6. Potential Applications of the Research

The compact soft X-ray laser is expected to have application in a number of areas important for DOD, such as material sciences and plasma diagnostics.

The Federal government has supported the generic development of the next generation of integrated circuits, which will have feature sizes of 200 nm or less, in order to maintain (or regain) US leadership in this crucial technology. The compact soft X-ray laser is expected to play an important role in the development of this technology. It should find applications in projection soft X-ray lithography: for testing X-ray optics and photoresists and for system alignment. The compact ("portable") soft X-ray laser will also be used as a radiation source for different types of X-ray microscopy. A soft X-ray reflection microscope, for example, could be used in high resolution analysis of defects in semiconductor devices.

The main advantages of the proposed SXL are relatively low cost, small size and high brightness. The SXL radiation is essentially monochromatic and can therefore be focused with small chromatic aberrations. This is very important, for example, for projection Soft X-ray lithography and imaging microscopy.

Compared to a laser plasma source, the SXR-laser is characterized by much higher directivity of the radiation: while the first radiates in 2π sr angle and only an insignificant part can be collected to expose an object, the last is characterized by radiation divergence $\sim 10^{-2}$ rad, even without use of a cavity. With a cavity, this parameter will be improved still more dramatically, by another three orders of magnitude.

In addition to the applications sketched above, successful completion of this work should provide a relatively compact, inexpensive, partially coherent soft X-ray radiation source with a beam energy of the order of 10-20 microjoules. This will allow researchers in "small science" environments (university, hospital and industrial laboratories) to perform novel experiments at relatively low cost and at a convenient pace. As a result, applications, which may be completely unanticipated at this time, should multiply as this unique radiation source becomes widely available. It is expected that it will stir scientific and industrial interest, resulting in financial support for commercial development in Phase III.

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